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CONTENTS

INTRODUCTION

Purpose

The penetration of objects into calcareous sands and the extraction of those objects is accomplished with much less effort than predicted by conventional techniques.* This phenomenon holds for driven piles, free-fall penetrometers, and explosively driven embedment anchors (to name a few such objects). Such low demonstrated resistances are probably due to several different factors, the contribution of each factor is unknown. The purpose of this research is to determine the contribution of one of these factors - the coefficient of friction - to these low demonstrated resistances.

Approach

Samples of calcareous sediments were collected, one from each of three environments: a foraminiferal** sand-silt from a deep-ocean site, an oolitic sand from a shallow-ocean site, and a coralline sand from an atoll beach. The coefficients of friction of these sands, and of a quartz sand used as a standard, against surfaces of rough and smooth mild steel and rough and smooth mortar were measured in a modified soils single direct shear test machine. Volume changes of the sands were measured as a function of sliding displacement across the steel and

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*Conventional techniques - empirically developed performance prediction techniques developed for common terrestrial soil materials, quartz and alumino-silicates.

**At times referred to as "foram."

mortar surfaces. Measured coefficients of friction and volume changes for the calcareous sands were then compared to those for the quartz sand.

Background

Calcareous Sediments. Calcareous sediments have proven troublesome to engineers, particularly in developing adequate pile capacity for offshore facilities (McClelland, 1974). Present engineering treatment of the problem simply imposes large factors of safety on the calculated ultimate pile capacity when in calcareous sediments in order to cope with the design uncertainty (American Petroleum Institute, 1976). Recent test results with propellant-driven plate embedment anchors have shown the foraminiferal type of calcareous sediment to be especially troublesome to the performance prediction of that type of plate embedment anchor (Valent, 1978).

The term "calcareous sediment" includes quite diverse materials differing in terms of origin, present location, exterior shape and strength of grains, and behavior under engineering loads. The calcareous grains in these sediments can be broadly classified into four groups, each with its own origin:

1. Ooliths - rounded, highly polished, and solid particles of calcium carbonate formed by chemical precipitation in warm, shallow seas

2. Fecal pellets - oblong, solid grains of calcite, probably originated as fecal pellets and were later cemented by carbonates (Bathurst, 1971)

3. Fossil tests and fragments - skeletal structures and fragments of structures of foraminifera and coccolithophorids, usually found in abundance in intermediate ocean depths

4. Coral and shell debris - silt, sand, and gravel size fragments of coral and shelled animals, found in near-shore areas of high productivity, with some relict and transported deposits found in quite deep water

Calcareous sediments generally classify as inorganic silts (MH) (for example, see Valent, 1974) or as inorganic sands (SM) in the Unified Soil Classification system. The adequacy of the Unified system to properly predict the engineering behavior of calcareous sediments is questioned; Fookes and Higginbottom (1975) have gone so far as to propose an alternate system to be used solely for calcareous sediments.

Limited field pile tests verify that driven piles in calcareous sediments offer significantly lower load capacities than those predicted using available design relationships (see Angemeer et al., 1975). On the basis of limited data, McClelland (1974) suggested limiting the assumed skin friction for driven piling in calcareous sediments to 400 psf (20 kPa). This limitation may reduce the allowable axial load capacity of a large, deep piling in calcareous sediments to one-fourth of that of the same size piling in largely quartz-grained sands. Limited field tests of propellant-driven plate embedment anchors in a foraminiferal calcareous sand-silt suggest that similar reductions (about 75%) in predicted holding capacities are appropriate (Valent, 1978).

<u>Causes of Low Capacities</u>. It is not readily apparent from the laboratory performance of these calcareous sediments that they would provide such inferior support for driven piles and plate embedment anchors. Measured angles of internal friction are 34 degrees or greater. At the beginning of this effort, it appeared that the low pile and anchor capacities stem from one or probably both of the following causes:

1. Insignificant increases in soil effective stresses resulting from the driving of piles and the keying of plate anchors, as compared

to those increases normally experienced in a quartz sand.* Possibly these effective soil stresses are not developing due to (a) the crushing or collapse of a cemented soil structure,** or (b) the crushing or breaking of the individual carbonate grains, especially as in the case of the foraminiferal sands and silts.**

2. Possible low magnitudes for the coefficients of friction developed between calcareous sediments and common building materials, as compared to friction coefficient magnitudes normally found with quartz-grained sands. Such a reduction in the coefficient of friction could be explained by the relative softness of the calcareous (carbonate) mineral (Moh's scale hardness of 3, compared to a hardness of 7 for quartz); and hence by the lesser ability of the calcareous material to engage, scratch, and abrade the surfaces of some building materials (e.g., steel with a Moh's scale hardness of 5).

This research effort was conceived as a means of identifying the more significant causes for the observed low friction coefficient values in calcareous sediments. The intent was to setup a test machine to measure directly the coefficient of friction between some typical examples of calcareous sediments (primarily sands and silts for ease of specimen preparation and test set-up) and some common building materials (i.e., concrete and steel), each in smooth and rough finishes. These measured coefficients of friction would then be compared to similarly measured coefficients between a quartz sand and these same building materials, and significant differences in the mobilized coefficients of friction for calcareous and quartz materials could be noted. Thus, a determination

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*The insignificant increases in the soil effective stresses, if such is the case, would result in lower soil shear strengths in the soil mass surrounding the pile or anchor - thence, in lower load capacities.

**The crushing of a cemented soil mass structure, especially if that structure was quite open (loose), and the crushing of hollow, egg-shell-like forams, although resulting in increased density of the specimen, need not result in increased effective stresses because the resulting structure after crushing would be looser than before.

would be made as to whether the very low load capacities of piles and anchors in calcareous materials is largely due to the friction coefficient developed by these materials against the building material or due to another cause - more specifically, due instead to low developed effective stresses arising from the breakdown of cemented bonds between soil grains or from the crushing of grains or both.

TESTING

Equipment

Testing was conducted in a modified direct shear test machine using circular specimens 2.5 inches (64 mm) in diameter (see, for example, Lambe, 1951, for detailed description of soils direct shear test equipment). Tests measuring the coefficients of friction on building materials were setup by substituting blocks of the building materials for the lower shear box, and then placing the upper shear box and upper half of a soil specimen on the surface of that building material specimen (Figure 1). Normal loads were applied to the sliding specimen surfaces through a deadload system. The normal load throughout the test series was maintained at 155.9 lbf (693.4 N). The upper box and soil specimen were moved across the lower box or building material specimen at 0.025 in./min (0.64 mm/min). In the first six tests, the shear load applied to the upper shear box was measured through a proving ring to the nearest 1 lbf (4 N). Horizontal displacements of the box and vertical expansion-contraction of the soil specimen for these six tests were measured via dial gauges to the nearest 0.001 in. (0.03 mm).

Mechanical measurement of the data via proving ring and dial gauges and hand-recording of that data, left much to be desired in terms of both the quality of the data points and the shape of the initial portion of the load-shear displacement curves. Problems arose because of the shear load-displacement behavior of the sands on the building materials:

the shear curve reached a peak within 0.025 in. (0.64 mm) of shear displacement, a time period of about 1 min from the start of testing. Since reading and recording the three dial gauges for one set of readings required about 20 sec, it was difficult to properly define this peak in the load-displacement curve. Furthermore, relaxation of the proving ring in the load measurement system after passing the peak load acted to distort and stretch out the load-displacement curve.

Because the mechanical measurement system did not prove satisfactory, that system was replaced by an electronic system with load monitored via a strain gage type of load cell to the nearest 0.1 lbf (0.4 N) and displacements monitored via LVDT's (linear variable differential transformers) to the nearest 0.001 in. (0.03 mm). All three channels of data were monitored and data sets printed on paper tape at prescribed time intervals. Thus, the electronic data measurement and recording system removed those shortcomings arising from the proving ring load measurement system and from the manual recording of data, while increasing the accuracy and usefulness of the data obtained.

Test Soils

Four soil materials, three calcareous sand/silts and one quartz sand (used as a reference) were employed in the test program. These materials are described below; grain size curves are presented in Figure 2.

Coralline Sand. A calcareous sand composed primarily of coral debris was obtained from the beach at Diego Garcia, an atoll in the Indian Ocean. The grains of this sand were solid and subrounded.*

Oolitic Sand. A sample of an aragonite sand composed primarily of ooliths, with a trace of gastropod shells and shell debris, was obtained from a commercial source mining the material from the Bahama Banks. The ooliths are near spherical, well-rounded,* and solid. The large shells

*For roundness classification see Pettijohn, 1949.

and shell fragments in the oolitic sand were removed for specimen preparation by using only that material passing the no. 20 sieve, U.S. Standard Sieve Series (passing 0.84 mm).

Foraminiferal Sand-Silt. The foraminiferal sand-silt included here was obtained from the Blake Plateau from a water depth of 1,200 meters as part of a study of the engineering properties of marine sediments (Lee, 1976). The grains of this sediment were primarily globular foraminifera tests (shells) and fragments thereof. The shells are well-rounded* and hollow with very thin walls; they are very susceptible to crushing during compression or shear distortion of the sediment.

Quartz Sand. The quartz sand used was a graded Ottawa sand, ASTM Designation C-109. Grains for this material are primarily rounded.*

Building Materials

Friction tests of these soil materials were conducted against two building materials, mild steel and a quartz sand mortar simulating concrete. Each of the two materials was tested in a "smooth" and in a "rough" surface finish.

Steel. Two blocks of a mild steel 105 x 115 x 29 mm thick were prepared to replace the lower specimen ring (see Figure 1) for the coefficient of friction tests. The friction surface of one of these blocks was not appreciably changed from that existing on the original rolled plate stock in the yard. Loose rust and scale were wire-brushed from the surface. This rough surfaced steel block was intended to simulate the surface of a steel displacement pile driven into the sand deposit. The friction surface of the second steel block was ground to near mirror-like finish and was maintained in that quality by repolishing

*For roundness classification see Pettijohn, 1949.

the surface after each test. This smooth surface was intended to represent the other end of the surface spectrum, somewhat like the polished surface of a gravity corer or a penetrometer.

Concrete. The mortar specimens were cast in the bottom of the shear box (Figure 1). The mortar mix was made using a uniformly graded quartz sand, ASTM Designation C-190, and Type II Portland Cement in the following proportions by weight:

Water/cement ratio, 0.45
Aggregate/cement ratio, 0.45

One mortar specimen was screeded until level, then allowed to cure for 20 hours, then wire-brushed to expose the sand aggregate, thus producing a "rough" concrete surface. The second specimen was cast against a plexiglass sheet to produce a very smooth surface. Friction testing on the rough concrete surface was begun 3 days after casting; and on the smooth concrete surface, 5 days after casting.

Procedure

For both the single direct shear tests on the sand materials and for the friction tests of sand on building materials, the soil materials were placed in the shear ring into de-ionized water.* The coralline, oolitic, and quartz materials were all in an air-dried condition before being placed in the water-filled shear ring; the foraminiferal sand-silt

*Beyond placing these materials through water with only minimal movement of the material for leveling purposes, no formal standardization of specimen placement was developed. Data were taken to establish specimen densities; however, no determinations of maximum and minimum densities were made. Establishing the relative densities of the specimens was thought not significant to the purpose of this effort; and, in any case, funds and time were not available for that degree of refinement. Suffice it to say then that the specimens were probably in a loose condition at the start of shear testing owing to their method of placement.

was maintained saturated prior to placement because air-drying removes the pore water from within the hollow shells after which the shells are very difficult to re-saturate. Before placement of the foraminiferal sand-silt, de-ionized water was added, and the sample was gradually and gently disaggregated and worked into a thick fluid consistency.

After compression under the normal load of 155.9 lbf (694 N) was essentially completed, the top shear ring was raised about 0.5 mm (0.02 in.) out of contact with the bottom shear ring or the building material specimen. Thus, friction between the brass of the top shear ring and the underlying surfaces was minimized.

TEST RESULTS

Format

Figures 3 through 7 present shearing load (F) and sample expansion-contraction data (ΔH) versus shear displacement. The shearing load F has been normalized by the normal load (N) acting on the shear surface. Thus the shearing load is represented in terms of the coefficient of friction (μ) when dealing with soil sample friction on a building material specimen, and in terms of tan ϕ when dealing with soil-soil shear, where ϕ is the angle of internal friction for the soil.

In some cases, shear and friction tests were repeated to verify or classify earlier test results, or to get an idea of the normal variation in data from specimen to specimen and test to test.

Sand-Sand Shear

The results of the direct shear tests are used herein primarily as a baseline from which to evaluate the friction performance of each sand material on the steel and concrete surfaces. The residual coefficients of friction ($\mu_{residual}$) are all noted as about the same magnitude, 0.54

to 0.61. The peak coefficients of friction (μ_{peak}) for the quartz, coralline, and foram sands are also noted as in a close grouping, 0.64 to 0.68. The μ_{peak} for the oolitic sand is somewhat higher, 0.77 and 0.81; these high μ_{peak} values may reflect some difference in the placement relative density.* The residual tan ϕ values for the calcareous sands are slightly higher than those for the quartz sand. For those comparisons made between duplicate tests on the same material (i.e., coralline and oolitic sands), the results from test to test are reasonably consistent.

The specimen volume change data of Figure 3 indicate a very slight initial decrease before reaching the peak friction angle, followed by a general volume increase for all of the sands with solid grains. On the other hand, the foraminiferal sand-silt, with its hollow-shell, easily crushed grains, exhibits a continuous and rather large decrease in volume during shear, presumably due to grain crushing.

Friction on Smooth Steel

Friction forces mobilized against the smooth (polished) mild steel are about one-third of those mobilized in internal shear of the sand. Very simply, the polished steel surface offers very few surface irregularities for the sand grains to engage. The coralline sand develops a rather consistent μ_{peak} of 0.20 and $\mu_{residual}$ of 0.17. The quartz sand develops slightly higher coefficients of friction, probably due to the somewhat harder quartz sand grains.

Results of the oolitic sand tests appear inconclusive. Results of the first test (no. 11) are quite low; results of the second test (no. 12) show a coefficient of friction more than twice the magnitude of the first. The difference in results can probably be explained by an unplanned difference in the preparation of the two specimens. Oolitic specimen no. 11 was tested whole with about 10% of the material by volume being

*Several other factors besides relative density affect the shape of the load-deflection curve (e.g., grain shape and hardness and grain size distribution); however, in this case these other parameters appear near equal.

larger than the no. 20 sieve, including gastropod and bi-valve shells and shell fragments up to 5 mm across. Specimen no. 12, on the other hand, was composed only of material passing the no. 20 sieve. Presumably the specimen with coarse material included (no. 11) transferred most of the normal load to the steel surface through these larger shell fragments, resulting in a lower overall coefficient of friction. This hypothesis assumes that the larger shells are less capable of developing friction force against the polished steel surface, than the smaller ooliths.

The foraminiferal sand-silt, no. 13, exhibits a higher coefficient of friction than the sands. This higher friction coefficient is believed due to the greater number of particle contacts engaging the smooth steel surface with the finer-grained, foram sand-silt specimen (no. 13).

Volume changes during sliding on the smooth steel are generally negligible, except for that of the foram sand-silt. Apparently the foram sand-silt undergoes considerable grain crushing even when sliding on the polished steel.

Friction on Rough Steel

Coefficients of friction developed on the rough steel are equal to those developed in the respective sands in internal shear, except for the oolitic sand. Sliding of the quartz, coralline, and foram sands on the rough steel is marked then by development of a shearing zone in the sand adjacent to the rough steel surface and is akin to internal shear of the sand. Full internal friction is not developed in the oolitic sand; the reason is unknown.

The foram sand-silt again undergoes considerable volume decrease during the initial portion of sliding/shear. The apparent volume increase noted in Figure 5 after 0.3-in. shear displacement is fictitious and results, instead, from tilting of the normal force ram in response to specimen distortion during sliding; i.e., the specimen is piled up at the trailing end of the shear ring (see Figure 1).

Friction on Smooth Concrete

Friction test results for the smooth concrete (Figure 6) and the rough steel appear nearly identical, even for the behavior of the oolitic sand. All of the above comments for rough steel apply here also.

Friction on Rough Concrete

The full frictional capacity of the sands is mobilized when they are slid on the rough concrete (Figure 7). No exceptional volume change behavior is noted.

EVALUATION

Coefficient of Friction

In general, these test results show that the low friction forces in calcareous sediments are not the result of low achievable coefficients of friction between calcareous sediments and building materials - as referenced to coefficients of friction between quartz sands and these same building materials. For the usual types of building material finishes (including, here, a rough steel and smooth and rough concretes), the full frictional capability of the calcareous sands can be - and was - developed. This frictional capability included frictional stresses to 160 kPa (3,400 psf), compared to the limit of 20 kPa (400 psf) recommended by McClelland (1974) based on field performance of piles. Note well, however, that friction force development is a two-component system; before a friction force can be developed, a normal force of required magnitude must exist. This point, and its relationship to McClelland's design maximum on friction stress magnitude, will be developed further in the next section.

It should be noted now that the developed coefficients of friction of all sands against the smooth, polished mild steel were about one-third those for each respective sand against the other building material specimens (Table 1). Smooth, polished steel surfaces are not usually employed in constructing a seafloor facility; however, various tools, especially survey tools, are regularly used; and some painted surfaces may perform in the sediments as smooth steel surfaces. Thus, when computing seafloor penetration depths, or when computing the force required to effect such penetrations, for smooth-skinned hardware, reductions on the order of 60% to 70% should be applied to the coefficient of friction as derived from soil shear tests.

Normal Force Development

The frictional force developed over a material surface is a function not only of the coefficient of friction of soil against material but also the effective normal force acting between the soil and that surface. In the testing herein the normal force was maintained constant by using the deadload system. In the field the normal load acting is a function of the stress state existing in the soil system before the penetrator enters, of the immediate densification of the soil by the penetrator and any accompanying increases in normal stresses, and of time-dependent relaxation of those normal stresses due to consolidation and shear creep. Since the data of this test program show that the coefficient of friction of calcareous sediments against steel and concrete surfaces is not markedly different from that of a quartz sand, then the demonstrated low frictional stresses in the field must have their cause in low developed normal stresses arising from penetration.

The foraminiferal sand-silt tested exhibits one possible cause for low developed normal forces. The volume change data of Figures 4, 5, and 6 indicate considerable volume decrease during development of the resisting friction force. Considering the nature of the grains, this volume decrease is probably largely due to crushing of the whole foram shells and further degradation of shell fragments. Penetration of a pile, for instance, in such a foram sediment would result in densification of the sediment, through crushing of the hollow shells, but such densification need not reflect increased effective stresses within the soil. The soil mass may just have been transformed from a loose pile of hollow shells to loose pile of shell fragments.

Following a similar line of reasoning, a hypothesis can be drawn for a cause of low effective stresses existing in deposits of other carbonate materials found on the seafloor; e.g., the oolitic and coralline sands also tested here. Cementing is known to occur in such deposits in modern seas; e.g., cemented oolitic sediments of the Red Sea and the beachrock of many coralline beaches. Undoubtedly, many other active cementing environments exist. In such a cementing environment, loose upper strata are quite likely to be lightly cemented at particle contacts. This loose, cemented structure could then support additional layers of sediment deposition without densifying or compacting. However, this same structure, on shearing during penetration (e.g., pile driving) would suffer breaking of cement bonds at grain contacts* and the loose grain structure would compact and densify. However, as with the hollow-shelled foram sand-silt, densification of such a loose structure does not necessarily mean increased internal effective stresses - rather the material moves into a closer but still loose packing.

CONCLUSIONS

1. The calcareous sediments tested, and presumably calcareous sediments in general, develop coefficients of friction against steel and concrete building materials that are comparable to those developed by quartz-type

*This concept is not new. It is being applied here to a slightly different situation than it has been in the past. Originally, a variant was proposed to explain the metastable behavior of Canadian quick clays.

sands. Thus, the possibility of low coefficients of friction being responsible for the observed low friction forces on driven piling and other penetrators in calcareous materials is ruled out.

2. The observed large volume decreases during shear of the foraminiferal sand-silt are probably responsible for the low developed friction forces in these hollow-shelled materials. Such large volume decreases at nonincreasing normal load imply densification in the field without accompanying increases in normal stress on the penetrator surface.

3. Low developed friction forces in other calcareous materials may arise from a similar mechanism involving a hypothesized loose, but cemented, structure for the soil material. The application of shear stresses during penetration would cause collapse of this structure to a denser, but still loose, arrangement.

RECOMMENDATION

Further clarification of the causes surrounding the low developed friction forces in calcareous sediments requires, at this time, further definition of the soil materials in which the low friction forces have been noted. This data survey should be atuned toward data on sediment constituents, including minor fractions; sediment structure; and remedial techniques, satisfactory and unsatisfactory, taken to produce the working design. This data collection will assist in describing the mechanism of the low friction phenomenon and, thereby, assist in identifying reliable and cost-effective solutions to Navy problems in calcareous sediments.

ACKNOWLEDGMENTS

Much of the testing and data reduction was very ably handled by Mr. Robert Sandoval, a co-op student at Ventura College. Oolitic sand used in the effort was very kindly supplied by Mr. Geoffrey Kellogg, Marcona

Ocean Industries, Fort Lauderdale, Fla. Coralline sand was provided by LCDR J. W. King, CEC, Officer-in-Charge, 30th Naval Construction Regiment Detachment, Diego Garcia. Foraminiferal sand-silt used herein was stored material obtained on a 1975 cruise of the USNS LYNCH, supported by the Naval Oceanographic Office and the Naval Facilities Engineering Command. This effort was made possible by the CEL's Independent Research funding, administered through the Director of Navy Laboratories.

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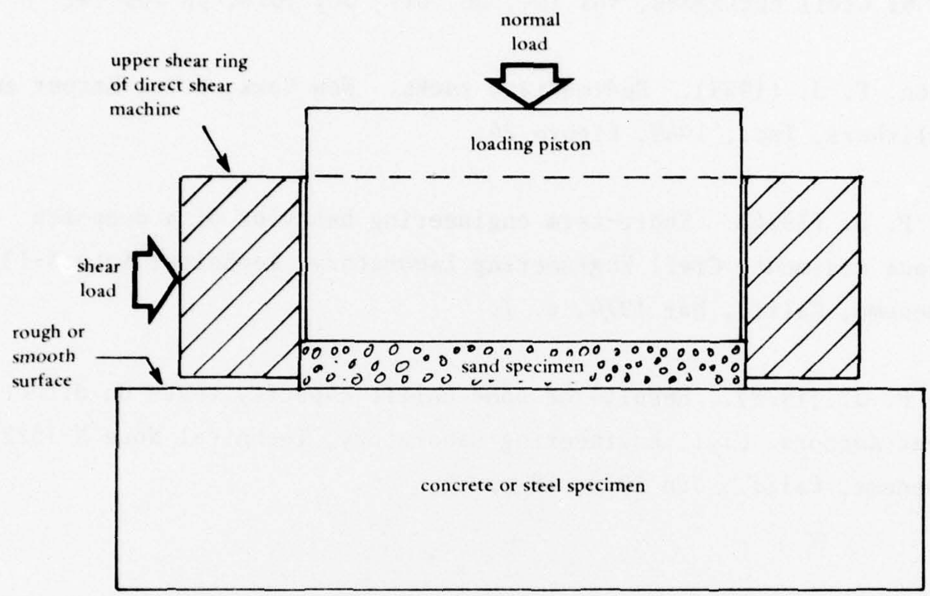

Figure 1. Specimen arrangement for tests of coefficients of friction.

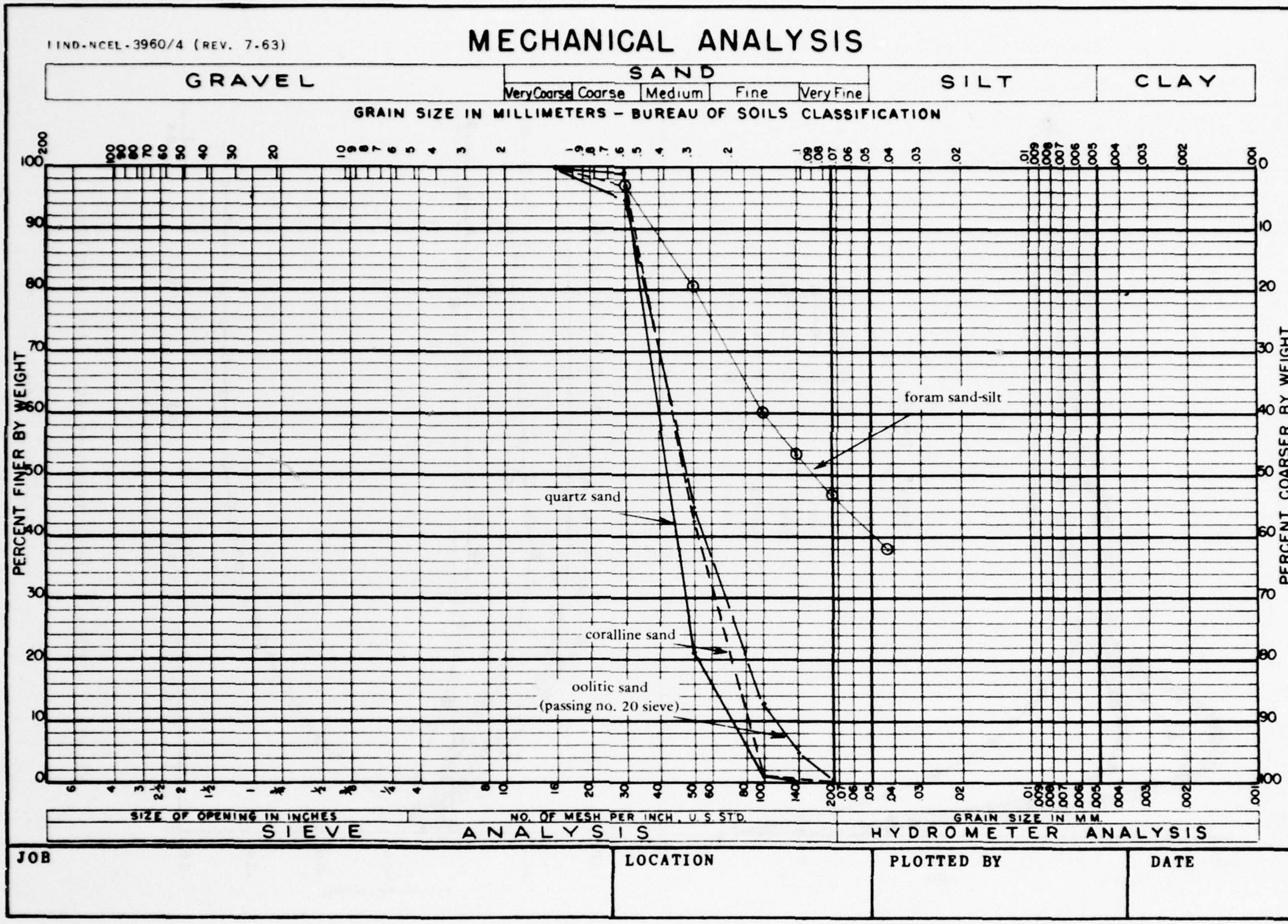

Figure 2. Grain size distribution of soil materials used.

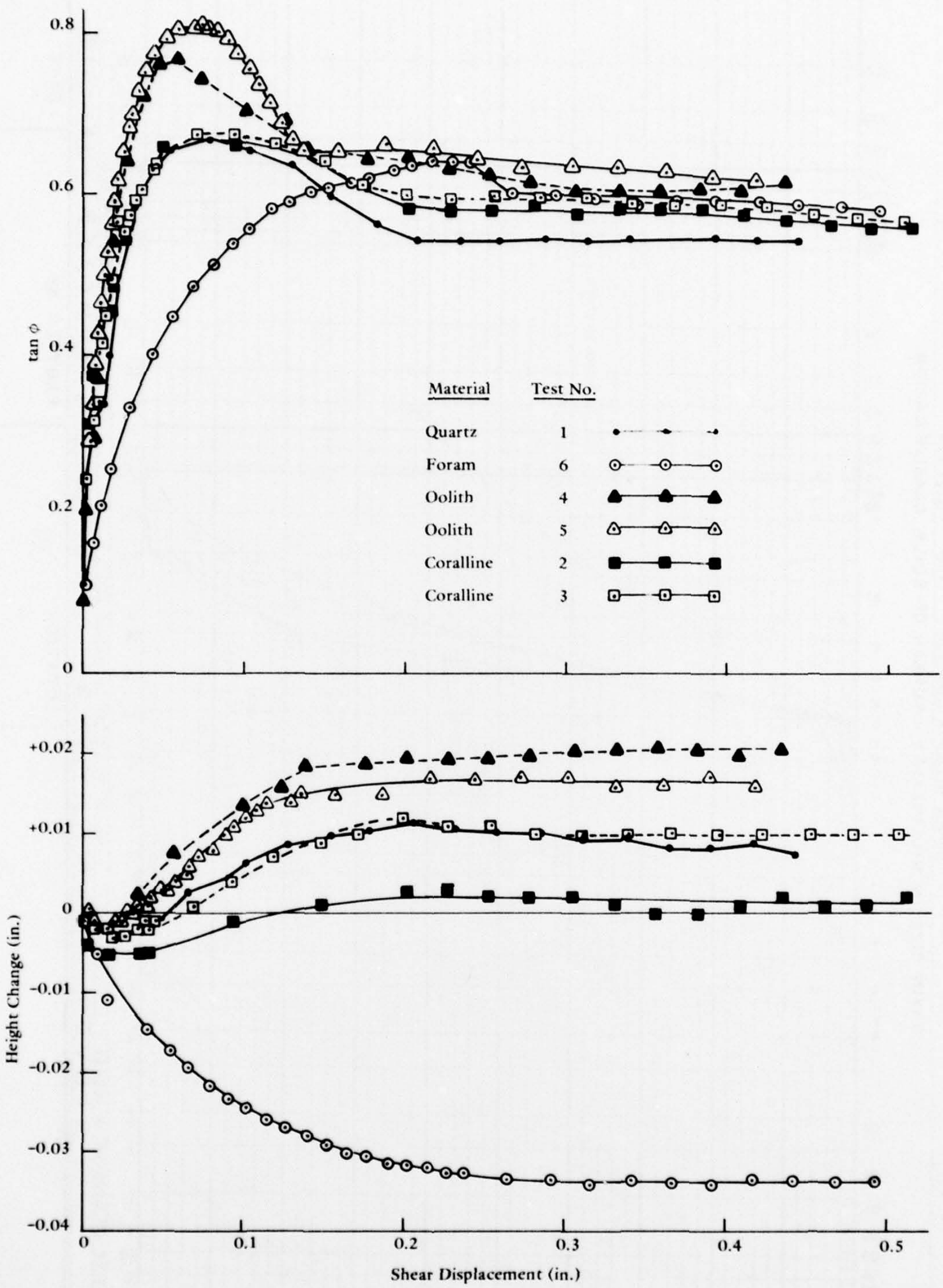

Figure 3. Direct shear tests on soil test samples.

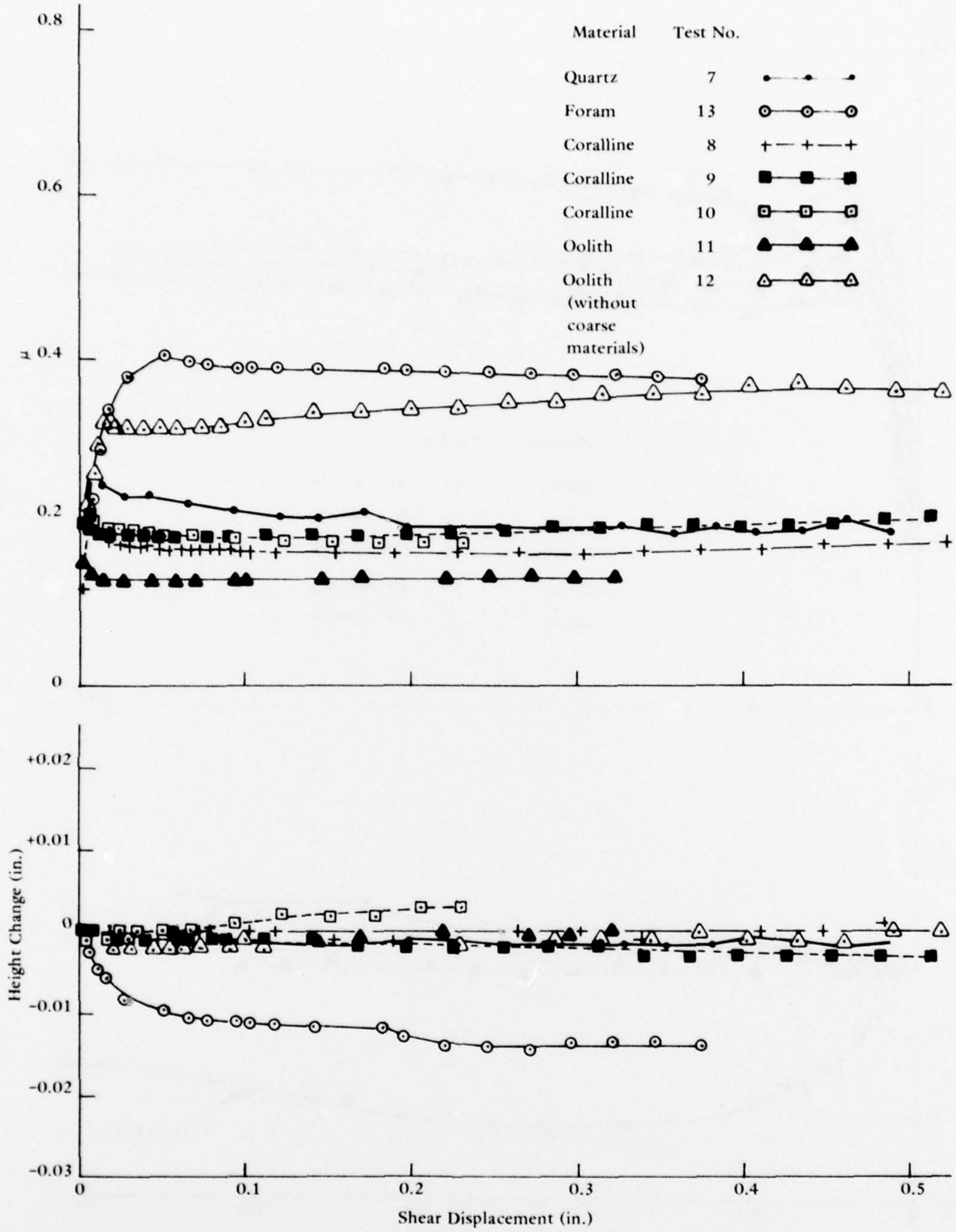

Figure 4. Friction tests of soil samples on smooth steel.

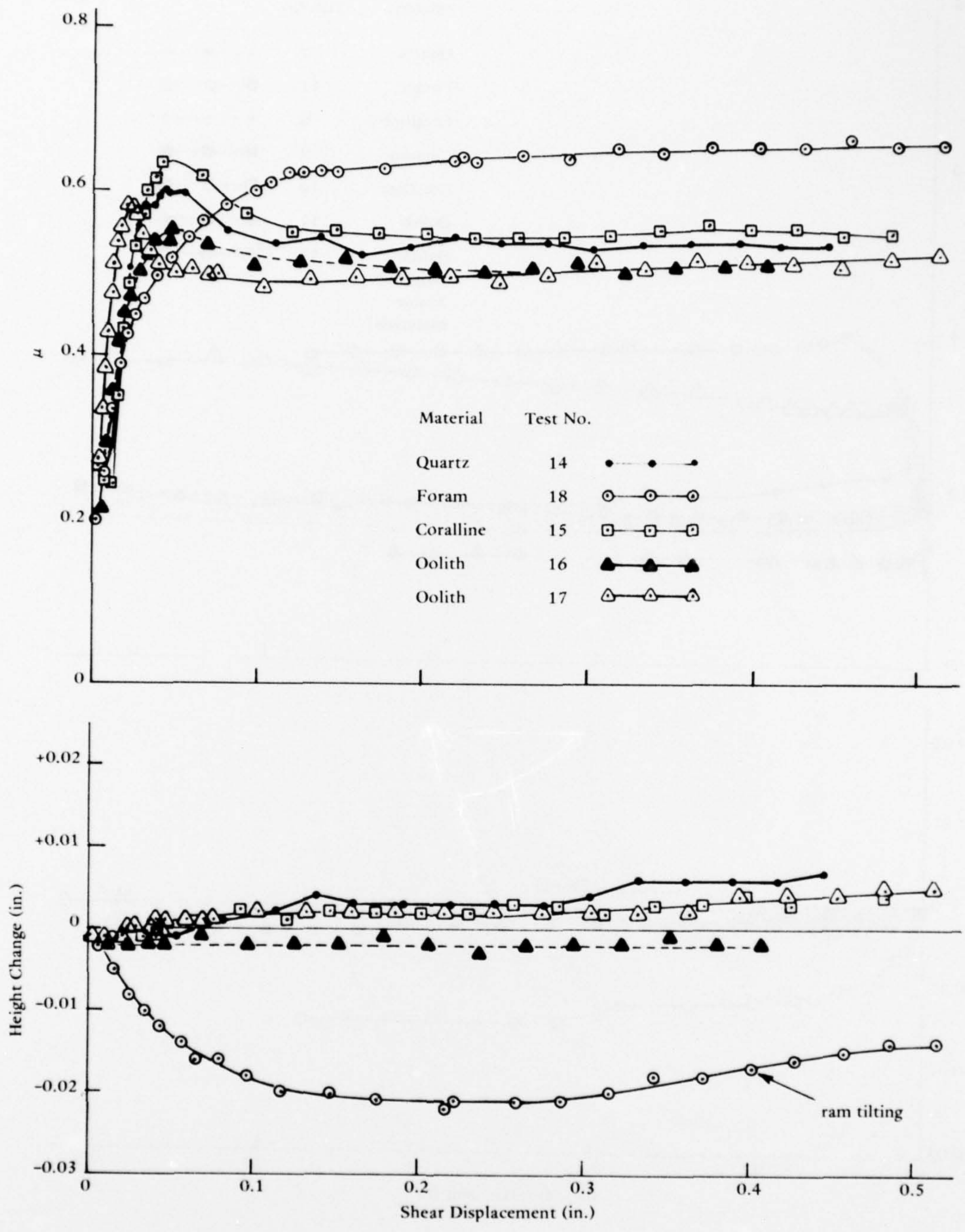

Figure 5. Friction tests of soil samples on rough steel.

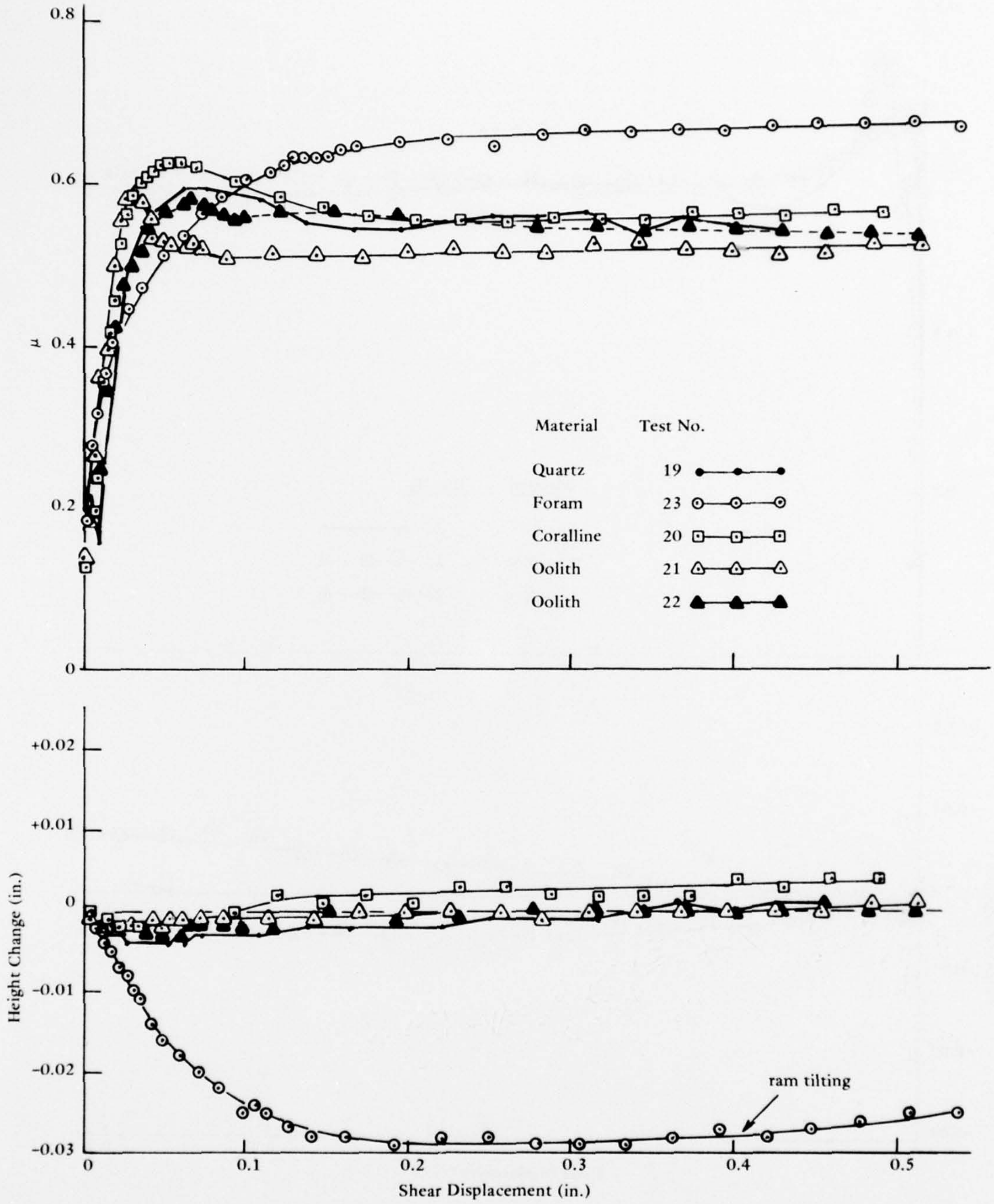

Figure 6. Friction tests of soil samples on smooth concrete.

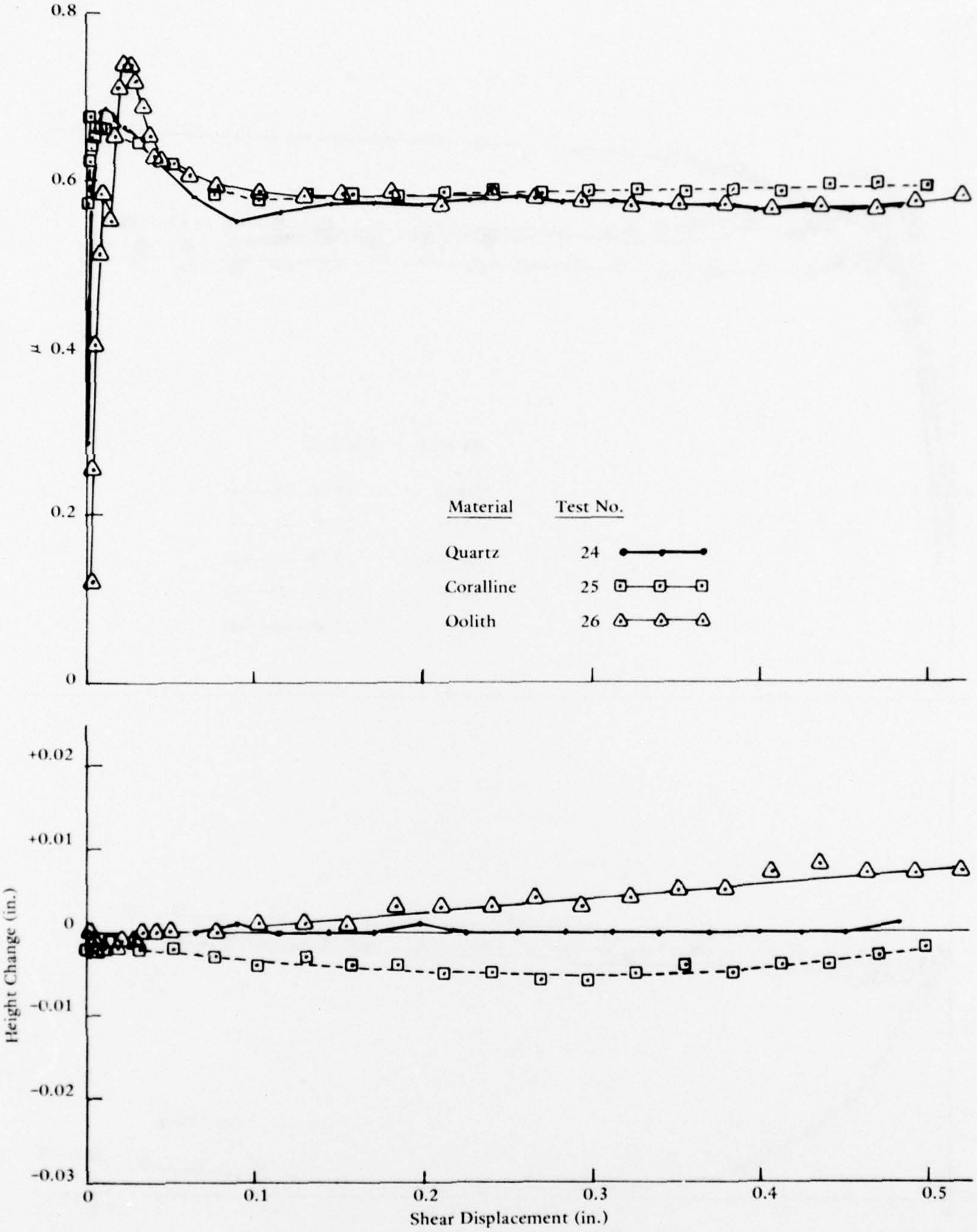

Figure 7. Friction tests of soil samples on rough concrete.

Table 1. Summary of Friction Test Results

Test No.	Base Material[a]	Soil Material	μ_{peak}[b]	$\mu_{residual}$[b]
1	Sand[c]	Quartz sand	0.67[d]	0.54
2	Sand	Coralline sand	0.66	0.56
3	Sand	Coralline sand	0.68	0.57
4	Sand	Oolitic sand	0.77[d]	0.61
5	Sand	Oolitic sand	0.81	0.62
6	Sand	Foram sand-silt	0.64[d]	0.58
7	Smooth steel	Quartz sand	0.27[d]	0.19
8	Smooth steel	Coralline sand	0.20	0.17
9	Smooth steel	Coralline sand	0.20	0.18[e]
10	Smooth steel	Coralline sand	0.21	0.17
11	Smooth steel	Oolitic sand	0.15[d]	0.13
12	Smooth steel	Oolitic sand	0.32	0.31
13	Smooth steel	Foram sand-silt	0.40	0.37
14	Rough steel	Quartz sand	0.60	0.54
15	Rough steel	Coralline sand	0.63	0.55
16	Rough steel	Oolitic sand	0.54	0.51
17	Rough steel	Oolitic sand	0.58	0.50
18	Rough steel	Foram sand-silt	----[f]	0.66
19	Smooth concrete	Quartz sand	0.60	0.54
20	Smooth concrete	Coralline sand	0.63	0.56
21	Smooth concrete	Oolitic sand	0.59	0.52
22	Smooth concrete	Oolitic sand	0.58	0.54
23	Smooth concrete	Foram sand-silt	----[f]	0.67
24	Rough concrete	Quartz sand	0.69	0.57
25	Rough concrete	Coralline sand	0.66	0.59
26	Rough concrete	Oolitic sand	0.74	0.57

[a]Soil in bottom shear ring for direct shear tests, or building material in friction tests.

[b]For direct shear tests $\mu = \tan \phi$ where ϕ = angle of internal friction; for friction tests $\mu = \tan \delta$ where δ = angle of sliding friction.

[c]Base material same as soil material for direct shear tests.

[d]These tests run with mechanical measurement system; i.e., proving ring and manual recording of data.

[e]Low value for μ reached shortly after μ_{peak}, thereafter μ increased with displacement to end of test.

[f]No peak μ reached, μ increasing through end of test.

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